DESCRIPTION

Pinion Shaft

Technical Field

The present invention relates to a pinion

5 shaft used for a steering device in a motor

vehicle, for example.

Background Art

An electric power steering device (EPS) is

preferable in energy conservation because the

10 fuel efficiency thereof can be improved by 3 to

5 %, compared with a hydraulic power steering

device.

Particularly, an electric power steering

device of a pinion assist type has the advantages

15 that a space where it is carried on a vehicle is

easier to ensure and the manufacturing cost

thereof is lower, as compared with an electric

power steering device of a rack assist type, and

it has spread mainly among compact cars.

20 In a conventional general pinion shaft, a

refined material that has been subjected to

quenching and tempering (refining treatment)

after rolling is machined. This causes a problem

of high manufacturing costs.

25 On the other hand, an attempt to obtain a

pinion shaft by performing machining without quenching and tempering (refining treatment) after rolling, and then performing surface hardening such as high frequency quenching has been made (see Japanese Patent No. 3036061, for example).

In the electric power steering device of a pinion assist type, stress and surface pressure that are exerted on a meshed portion of a rack bar serving as a steering shaft extending in the horizontal direction of an automobile and a pinion are significantly higher (e.g. six to ten times), as compared with those in the hydraulic power steering device.

On the other hand, even in the electric power steering device of a pinion assist type, a pinion shaft having specifications common to a pinion shaft used in the hydraulic power steering device may, in many cases, be used in order to reduce the cost due to a quantity production effect by making components common to both of the steering devices. Therefore, cars that are larger in size than mid-size vehicles on which high stress and high surface pressure are exerted are at a disadvantage in wear resistance, strength (including static

torsional strength and torsional fatigue strength), and toughness. As a result, the employment of the electric power steering device is liable to be limited to compact vehicles.

5   An object of the present invention is to provide a pinion shaft which is low in cost and capable of withstanding high stress and high surface pressure.

Disclosure of Invention

10   In order to attain the above-mentioned object, the present invention provides a pinion shaft formed using a non-refined steel as a material. The pinion shaft comprises a shaft section and a pinion teeth forming section

15   connecting with the shaft section, the pinion teeth forming section comprising pinion teeth and a tooth bottom, the pinion teeth forming section and the shaft section being provided with a hardened layer that has been subjected to high

20   frequency quenching and tempering, the steel containing 0.45 to 0.55 % by mass of C, 0.10 to 0.50 % by mass of Si, 0.15 to 0.25 % by mass of Mo, 0.0005 to 0.005 % by mass of B, and the surface hardnesses of the pinion teeth forming section and

25   the shaft section being 650 to 760 HV in terms of

Vickers hardness.

The reason why the surface hardnesses of the pinion teeth forming section and the shaft section are limited to 650 to 760 HV is as follows. That

5 is, when the surface hardness is less than 650 HV, the surface hardness of the pinion teeth forming section is not sufficient, and the wear resistance of a rack used in combination therewith is low. On the other hand, when the surface hardness

10 exceeds 760 HV, the toughness of a surface layer is deteriorated, and static torsional strength is insufficient. Therefore, the surface hardnesses of the pinion teeth forming section and the shaft section are set to 650 to 760 HV to improve the

15 wear resistance of the rack as well as to ensure sufficient torsional strength for a static load. The preferable lower limit values of the surface hardnesses of the pinion teeth forming section and the shaft section are 680 HV. The upper limit

20 values are preferably 730 HV, and more preferably 710 HV.

It is preferable that the steel further contains 0.5 to 1.2 % by mass of Mn.

It is preferable that the steel further

25 contains at least one type selected from not more

than 0.5 % by mass of Cr, not more than 0.5 % by mass of Cu, and not more than 0.5 % by mass of Ni.

It is preferable that the steel further contains not more than 0.025 % by mass of P, not more than 0.025 % by mass of S, 0.005 to 0.10 % by mass of Ti, and not more than 0.015 % by mass of N, and satisfies the following equations 1 and 2, respectively representing the contents (% by mass) of C, Si, Mn, Cr, Mo, Cu, Ni, and Cr by $a(C)$, $a(Si)$, $a(Mn)$, $a(Cr)$, $a(Mo)$, $a(Cu)$, $a(Ni)$, and $a(Cr)$, the residual being composed of Fe and inevitable impurities.

Equation 1・・・$0.80 \leqq Ceq \leqq 0.95$

where $Ceq = a(C) + 0.07 \times a(Si) + 0.16 \times a(Mn)$
$+ 0.20 \times a(Cr) + 0.72 \times a(Mo)$

Equation 2・・・$f \, value \leqq 1.0$

where $f \, value = 2.78 - 3.2 \times a(C) + 0.05 \times a(Si) - 0.60 \times a(Mn) - 0.55 \times a(Cu) - 0.80 \times a(Ni) - 0.75 \times a(Cr)$

It is desirable that in order to ensure the tool life in machining of the pinion shaft and the strength of the pinion shaft, the hardness in a steel serving as an inclusion for production after hot rolling for forming the pinion shaft is 24 to 30 HRC. The reason for this is that strength

required for the pinion shaft is not obtained when the hardness is less than 24 HRC, while the tool life is reduced to increase the cost, requiring a time period for machining when the hardness

5 exceeds 30 HRC.

On the other hand, in the case of a steel for the pinion shaft, the size of the steel material is 20 to 30 mm, hot rolling conditions are a draft ratio at an area reduction ratio of not less than

10 10 % at a temperature of not more than 850℃, and a cooling method is relatively low-cost air blast cooling, atmospheric cooling, or pivot cooling. Accordingly, the hardness of the steel after hot rolling almost depends on the magnitude of Ceq.

15 In order that the hardness may be 24 to 30 HRC, described above, Ceq must be set to 0.80 to 0.95. The reason for this is that the hardness after hot rolling does not reach 24 HRC when Ceq is less than 0.80, while it is higher than 30 HRC, making the

20 steel too hard, deteriorating the machinability, and thereby deteriorating tooth form accuracy when Ceq is more than 0.95.

Similarly, in the case of the steel for a pinion shaft, the ferrite amount therein almost

25 depends on the magnitude of the f value. In order

that the ferrite amount may be a ferrite area ratio
of not more than 40 % required as the steel for
a pinion shaft, the f value must be set to not more
than 1.0.   The reason for this is as follows.

5   That is, when a large amount of ferrite exists
in a tissue before high frequency quenching, C is
not sufficiently diffused into the ferrite in heat
treatment for a short time, for example, high
frequency quenching, and the ferrite remains in
10   the tissue after high frequency quenching.   The
remaining ferrite causes the bending and
torsional strength to be reduced.   Further,
uniform hardness is not easily obtained, and the
wear resistance is also deteriorated.

15   It is considered that in order to reduce the
amount of the remaining ferrite, heating for a
long time and heating at high temperature is
performed in high frequency quenching.   When
heating for a long time is performed, however, the
20   depth of a hardened layer is too deep, which causes
the strain of the pinion shaft to be manufactured
to be increased and causes the fatigue strength
to be reduced due to the reduction in residual
stress in the vicinity of a surface.   On the other
25   hand, when heating at high temperature is

performed, crystal grains in a high frequency quenched layer are coarsened, which leads to deterioration of the toughness. Consequently, it is desirable that the ferrite amount before high

5 frequency quenching is not more than 40 %. For that purpose, the f value is set to not more than 1.0.

In the present invention, it is preferable that the ratio D/R of the effective case depth D

10 in the tooth bottom (corresponding to a depth to an area 450 HV apart from the surface) to the radius R of the tooth bottom is 0.1 to 0.5. When the ratio D/R exceeds 0.5, the strain of the pinion teeth is increased. On the other hand, when the

15 ratio D/R is less than 0.1, the static torsional strength and the torsional fatigue strength of the pinion teeth are liable to be insufficient. Therefore, the ratio D/R is set in a range of 0.1 to 0.5 to prevent the strain of the pinion teeth

20 while ensuring the static torsional strength and the torsional fatigue strength of the pinion teeth. The preferable lower limit value of the ratio D/R is 0.2, and the more preferable upper limit value thereof is 0.4.

25 In the present invention, it is preferable

that the ratio d/r of the effective case depth d
in the shaft section to the radius r of the shaft
section is 0.05 to 0.6. In a case where the ratio
d/r is less than 0.05, the static torsional

5 strength and the torsional fatigue strength of the
shaft section are liable to be insufficient, and
a fatigue fracture at an inner starting point is
liable to occur. On the other hand, when the ratio
d/r exceeds 0.7, the toughness is deteriorated,

10 and the manufacturing cost is high, which is not
practical. Therefore, the ratio d/r is set in a
range of 0.05 to 0.6 to ensure the toughness while
ensuring the static torsional strength and the
torsional fatigue strength of the shaft section.

15 The preferable lower limit value of the ratio d/r
is 0.35. The more preferable upper limit value
of the ratio d/r is 0.5. In the case of the
above-mentioned pinion shaft, high wear
resistance and high strength (static strength,

20 fatigue strength, impact strength) can be
achieved using a low-cost non-refined steel.
Therefore, the pinion shaft can be suitably used
for a high-power electric power steering device
of a pinion assist type that receives high stress

25 and high surface pressure.

Brief Description of Drawings

Fig. 1 is a schematic view of an electric power steering device of a pinion assist type to which a pinion shaft according to an embodiment of the present invention is applied.

Fig. 2 is a cross-sectional view of the pinion shaft.

Fig. 3 is a cross-sectional view taken along a line III - III shown in Fig. 2.

Fig. 4 is a cross-sectional view taken along a line IV - IV shown in Fig. 2.

Fig. 5 is a schematic view of a tester for a positive input static fracture test.

Fig. 6 is a schematic view of a tester for a reverse input static fracture test.

Fig. 7 is a schematic view of a tester for a reverse input impact test.

Fig. 8 is a schematic view of a tester for a positive input durability test.

Fig. 9 is a schematic view of a tester for a reverse input durability test.

Best Mode for Carrying Out the Invention

A preferred mode of the present invention will be described while referring to the accompanying drawings.

Fig. 1 is a schematic view of an electric
power steering device using a steering rack
according to an embodiment of the present
invention. Referring to Fig. 1, an electric power
5   steering device (EPS : Electric Power Steering
System) 1 has a steering shaft 3 connected to a
steering member 2 such as a steering wheel, an
intermediate shaft 5 connected to the steering
shaft 3 through a universal joint 4, a pinion shaft
10   7 connected to the intermediate shaft 5 through
a universal joint 6, and a rack bar 8 serving as
a steering shaft having rack teeth 8a meshed with
pinion teeth 7a provided in the vicinity of an end
of the pinion shaft 7 and extending in the
15   horizontal direction of a motor vehicle.

The rack bar 8 is supported so as to be
linearly movable back and forth through a
plurality of bearings (not shown) within a housing
9 fixed to a vehicle body. Both ends of the rack
20   bar 8 project on both sides from the housing 9,
and a tie rod 10 is coupled to each of the ends.
Each of the tie rods 10 is connected to a
corresponding steerable wheel 11 through a
corresponding knuckle arm (not shown).

25   When the steering member 2 is operated so that

the steering shaft 3 is rotated, the rotation is converted into the linear motion of the rack bar 8 in the horizontal direction of the motor vehicle by the pinion teeth 7a and the rack teeth 8a.

5   Consequently, the steering of the steerable wheel 11 is achieved.

The steering shaft 3 is divided into an input shaft 3a connecting with the steering member 2 and an output shaft 3b connecting with the pinion

10   shaft 7.   The input and output shafts 3a and 3b are connected to each other so as to be relatively rotatable on the same axis through a torsion bar 12.

There is provided a torque sensor 13 for

15   detecting a steering torque by an amount of displacement by relative rotation between the input and output shafts 3a and 3b through the torsion bar 12.   The results of the detection of the torque by the torque sensor 13 are given to

20   an ECU (Electronic Control Unit) 14.   The ECU 14 controls an applied voltage to an electric motor 16 for steering assist through a driving circuit 15 on the basis of the results of the detection of the torque, the results of the detection of a

25   vehicle speed given from a vehicle speed sensor

(not shown), and so forth. The output rotation of the electric motor 16 is decelerated through a speed reduction mechanism 17 and is transmitted to the pinion shaft 7, and is converted into the
5 linear motion of the rack bar 8, assisting in steering.

Exemplified as the speed reduction mechanism 17 is a gear mechanism comprising a pinion 17a such as a worm shaft connected to a rotating shaft (not
10 shown) of the electric motor 16 so as to be integrally rotatable and a wheel 17b such as a worm wheel meshed with the pinion 17a and connected to the pinion shaft 7 so as to be integrally rotatable.

15 Fig. 2 is a cross-sectional view of the pinion shaft, Fig. 3 is a cross-sectional view taken along a line III - III shown in Fig. 2, and Fig. 4 is a cross-sectional view taken along a line IV - IV shown in Fig. 2. Referring to Fig. 2, the
20 pinion shaft 7 comprises a pinion teeth forming section 70, and a pair of shaft sections 71 and 72 extending coaxially with an axis 90 on both sides of the pinion teeth forming section 70. The shaft section 71 is composed of a long shaft, and
25 is arranged on the side of the intermediate shaft

5. The shaft section 72 is composed of a short shaft.

Referring to Fig. 3, the pinion teeth forming section 70 comprises a plurality of pinion teeth 7a formed with equal spacing in the circumferential direction, and a tooth bottom 7b interposed between the adjacent pinion teeth 7a.

The pinion shaft 7 is machined using a low-cost non-refined steel as a material so that the shape thereof is formed, and is then subjected to high frequency quenching and tempering. Consequently, as shown in Figs. 2, 3 and 4, the pinion teeth forming section 70 and the shaft sections 71 and 72 are provided with a hardened layer 80 that has been subjected to high frequency quenching and tempering as surface hardening, and a difference in hardness is provided between the hardened layer 80 and a shaft interior 81 inside thereof.

The steel contains 0.45 to 0.55 % by mass of C, 0.15 to 0.25 % by mass of Mo, and 0.0005 to 0.005 % by mass of B.

The non-refined steel containing 0.45 to 0.55 % by mass of C is subjected to high frequency quenching so that wear resistance and toughness

required as a pinion shaft are provided thereto. That is, when the C content is not less than 0.45 % by mass, the wear resistance of the pinion shaft 7 can be enhanced by high frequency quenching. On the other hand, when the C content exceeds 0.55 % by mass, the impact resistance is deteriorated, and quenching cracks are liable to occur at the time of high frequency quenching. Therefore, the C content is set in the range of 0.45 to 0.55 % by mass.

Addition of Mo enhances the hardenability, strengthens the inside of a crystal grain boundary, and improves the resistance to the action of impact stress in the hardened layer 80 obtained by high frequency quenching, thereby allowing the occurrence of cracks due to impact to be suppressed. For that purpose, not less than 0.15 % by mass of Mo must be contained. If the Mo content is high, however, martensite is produced in a rolled state, and the steel becomes hard, thereby deteriorating the machinability. Therefore, the upper limit of the Mo content is set to 0.25 % by mass. Particularly, Mo is added in combination with B, and hardening for improving the toughness of the hardened layer 80 obtained

by high frequency quenching is further promoted.

B suppresses grain boundary segregation of P that is an inevitable impurity to strengthen a grain boundary, thereby allowing the toughness of

5 the hardened layer 80 to be improved. For that purpose, not less than 0.0005 % by mass of B must be contained. If the B content is too high, however, crystal grains are coarsened to deteriorate the toughness. Therefore, the upper

10 limit of the B content is set to 0.005 % by mass.

As the other components, the steel contains 0.10 to 0.50 % by mass of Si, 0.50 to 1.20 % by mass of Mn, not more than 0.025 % by mass of P, not more than 0.025 % by mass of S, not more than

15 0.50 % by mass of Cu, not more than 0.50 % by mass of Ni, not more than 0.50 % by mass of Cr, 0.005 to 0.1 % by mass of Ti, and not more than 0.015 % by mass of N, and the remaining components are Fe and inevitable impurities.

20 Since Si has a deoxidation action in melting the steel, it is an element to be contained for that purpose. In order to obtain the action and effect, not less than 0.10 % by mass of Si must be contained. If the Si content is too high,

25 however, the toughness of the steel is

deteriorated. Therefore, the upper limit of the Si content is set to 0.50 % by mass.

Since Mn has a deoxidation action in melting the steel and improves the hardenability of the steel, it is an element to be contained for that purpose. In order to obtain the action and effect, not less than 0.50 % by mass of Mn must be contained. If the Mn content is too high, the hardness of the steel becomes too high. Therefore, the upper limit of the Mn content is set to 1.2 % by mass.

P is an inevitable impurity, and is an element for reducing the toughness by grain boundary segregation as well as promoting the occurrence of quenching cracks in high frequency quenching. Therefore, it is preferable that the P content is low. Even if the P content is reduced, however, the effect is saturated, and the cost is high. Therefore, the upper limit of the P content is set to 0.025 % by mass.

S is an inevitable impurity, and forms a sulfide inclusion to be a starting point of a fatigue fracture, thereby reducing the fatigue strength. Further, it causes the occurrence of quenching cracks. Consequently, it is preferable

that the S content is low. If the S content becomes
significantly low, the machinability is
deteriorated. Therefore, the upper limit of the
S content is set to 0.025 % by mass.

5   Since Ti forms TiN to fix N in the steel and
prevents the production of BN to increase the
effective amount of B, it is an element to be
contained for that purpose. In order to fix N to
exhibit the effect of B, not less than 0.005 % by

10 mass of N must be contained. If the N content is
too high, the toughness is deteriorated.
Therefore, the upper limit of the N content is set
to 0.10 % by mass.

       N is an inevitable impurity, and forms a

15 nitride non-metal in the steel to reduce the
fatigue strength. Therefore, the upper limit of
the N content is set to 0.015 % by mass.

       Cu may be contained in order to control the
f value. When the Cu content is high, however,

20 the hot workability of the steel is deteriorated.
Therefore, the upper limit of the Cu content is
set to 0.50 % by mass.

       Ni may be contained in order to control the
f value. When the Ni content is high, however,

25 the machinability of the steel is deteriorated.

Therefore, the upper limit of the Ni content is set to 0.50 % by mass.

Cr may be contained in order to control the f value. When the Cr content is high, however,
5   the hardenability of the steel is increased, and martensite is produced in a rolled state. Therefore, the hardness is too high, to deteriorate the machinability. Therefore, the upper limit of the Cr content is set to 0.50 % by
10   mass.

Since Nb and Ta refine the tissue of the high frequency quenched layer to improve the toughness, they are elements to be contained for that purpose. If the Nb and Ta contents are high,
15   the effect is saturated. Therefore, the upper limits of the Nb and Ta contents are set to 0.20 % by mass.

Since Zr refines the tissue of the high frequency quenched layer to improve the
20   toughness, forms an oxide as a nucleous of a sulfide, and improves the extensibility of MnS to form a granular sulfide, thereby improving the torsional fatigue strength, it is an element to be contained for that purpose. If the Zr content
25   is high, however, the effect is saturated.

Therefore, the upper limit of the Zr content is set to 0.10 % by mass.

Since Al has a strong deoxidation action in melting the steel and refines crystal grains to improve the toughness, it is an element to be contained for that purpose. If the Al content is too high, however, the amount of an Al_2O_3 inclusion is increased to reduce the fatigue strength. Therefore, the upper limit of the Al content is set to 0.10 % by mass.

It is preferable that the above-mentioned steel satisfies the following equations 1 and 2, respectively representing the contents (% by mass) of C, Si, Mn, Cr, Mo, Cu, Ni, and Cr by a(C), a(Si), a(Mn), a(Cr), a(Mo), a(Cu), a(Ni).

Equation 1 · · · 0.80 $\leqq$ Ceq $\leqq$ 0.95

where Ceq = a(C) + 0.07 × a(Si) + 0.16 × a(Mn)

+ 0.20 × a(Cr) + 0.72 × a(Mo)

Equation 2 · · · f value $\leqq$ 1.0

where f value = 2.78 - 3.2 × a(C) + 0.05 × a(Si) - 0.60 × a(Mn)

- 0.55 × a(Cu) - 0.80 × a(Ni) - 0.75 × a(Cr)

It is desirable that in order to ensure the tool life in machining of the pinion shaft and the strength of the pinion shaft, the hardness in an

inclusion for production after hot rolling for
forming the pinion shaft is 24 to 30 HRC. The
reason for this is that strength required for the
pinion shaft is not obtained when the hardness is
5 less than 24 HRC, while the tool life is reduced
to increase the cost, requiring a time period for
machining when the hardness exceeds 30 HRC.

On the other hand, in the case of a steel for
the pinion shaft, the size of the steel material
10 is 20 to 30 mm, hot rolling conditions are a draft
ratio at an area reduction ratio of not less than
10 % at a temperature of not more than 850°C, and
a cooling method is relatively low-cost air blast
cooling, atmospheric cooling, or pivot cooling.
15 Accordingly, the hardness of the steel after hot
rolling almost depends on the magnitude of Ceq.
In order that the hardness may be 24 to 30 HRC,
described above, Ceq must be 0.80 to 0.95. The
reason for this is that the hardness after hot
20 rolling does not become not less than 24 HRC when
Ceq is less than 0.80, while it is higher than 30
HRC, making the steel too hard, deteriorating the
machinability, and thereby deteriorating tooth
form accuracy when Ceq is more than 0.95.

25   Similarly, in the case of the steel for a

pinion shaft, the ferrite amount therein almost depends on the magnitude of the f value. In order that the ferrite amount may be a ferrite area ratio of not more than 40 % required as the steel for

5 a pinion shaft, the f value must be set to not more than 1.0.

When a large amount of ferrite exists in a tissue before high frequency quenching, C is not sufficiently diffused into the ferrite in heat

10 treatment for a short time, for example, high frequency quenching, and the ferrite remains in the tissue after high frequency quenching. The residual ferrite causes the bending and torsional strength to be reduced. Further, uniform hardness

15 is not easily obtained, and the wear resistance is also deteriorated.

It is considered that in order to reduce the amount of the residual ferrite, heating for a long time or heating at high temperature is performed

20 in high frequency quenching. When heating for a long time is performed, however, the depth of a hardened layer is too high, which causes the strain of the pinion shaft to be manufactured to be increased and causes the fatigue strength to

25 be reduced due to the reduction in residual stress

in the vicinity of a surface. On the other hand, when heating at high temperature is performed, crystal grains in a high frequency quenched layer are coarsened, which leads to deterioration of the

5   toughness. Consequently, it is desirable that the ferrite amount before high frequency quenching is not more than 40 %. For that purpose, the f value is set to not more than 1.0.

It is preferable that the tissue after hot

10   rolling is a three-phase texture of ferrite + perlite + bainite. The reason for this is that when martensite exists, the hardness after hot rolling becomes significantly high, and the impact value is reduced.

15   Furthermore, it is preferable that the maximum perlite block size in the tissue after hot rolling is not more than 100 μm in terms of a circle-equivalent diameter for the following reasons. That is, in order to suppress the

20   occurrence of peeling at the time of hobbing, it is effective to refine the tissue. This is because peeling occurs by stripping at the time of hobbing particularly if a perlite block is coarse. Considering the surface finish accuracy of a

25   practical pinion shaft, it is preferable that the

circle-equivalent diameter of the perlite block is set to not more than 100 µm.

The surface hardnesses of the pinion teeth forming section 70 and the shaft sections 71 and 72 are set to 650 to 760 HV. The reason for this is that the surface hardness of the pinion teeth forming section 70 is not sufficient, and the wear resistance of a rack used in combination therewith is low when the surface hardness is less than 650 HV, while the toughness of a surface layer is deteriorated, and the static torsional strength is insufficient when the surface hardness exceeds 760 HV. Therefore, the surface hardnesses of the pinion teeth forming section 70 and the shaft sections 71 and 72 are set to 650 to 760 HV to enhance the wear resistance of the rack as well as to ensure sufficient torsional strength for a static load. The preferable lower limit values of the surface hardnesses of the pinion teeth forming section 70 and the shaft sections 71 and 72 are 680 HV, and the more preferable upper limit values thereof are 710 HV.

Referring to Fig. 3, the ratio (hardened layer ratio) D/R of the effective depth of the hardened layer 80 in the tooth bottom 7b, that is,

the effective case depth D in the tooth bottom 7b (corresponding to a depth to an area 450 HV apart from the surface) to the radius R of the tooth bottom 7b is set in a range of 0.1 to 0.5. When the ratio D/R exceeds 0.5, the strain of the pinion teeth is increased. On the other hand, when the ratio D/R is less than 0.1, the static torsional strength and the torsional fatigue strength of the pinion teeth are liable to be insufficient. Therefore, the ratio D/R is set in a range of 0.1 to 0.5 to prevent the strain of the pinion teeth 7a while ensuring the static torsional strength and the torsional fatigue strength of the pinion teeth 7a. The preferable lower limit value of the ratio D/R is 0.2, and the preferable upper limit value thereof is 0.4.

Referring to Fig. 4, the ratio (hardened layer ratio) d/r of the effective depth of the hardened layer 80 in the shaft sections 71 and 72, that is, the effective case depth d in the shaft sections 71 and 72 to the radius r of the shaft sections is set in a range of 0.05 to 0.6. In a case where the ratio d/r is less than 0.05, the static torsional strength and the torsional fatigue strength of the shaft sections 71 and 72

are liable to be insufficient, and a fatigue
fracture at an inner starting point is liable to
occur. On the other hand, when the ratio d/r
exceeds 0.6, the toughness is deteriorated, and

5   the manufacturing cost is high, which is not
practical. Therefore, the ratio d/r is set in a
range of 0.05 to 0.6 to ensure the toughness and
the practicability in cost while ensuring the
static torsional strength and the torsional

10 fatigue strength of the shaft sections 71 and 72.
The preferable lower limit value of the ratio d/r
is 0.35. The more preferable upper limit value
of the ratio d/r is 0.5.

It is preferable that in the pinion teeth

15 forming section 70 and the shaft sections 71 and
72, the Vickers hardness in a portion deeper than
the hardened layer 80 is 260 to 300 HV. When the
hardness of a shaft interior 81 is less than 260
HV, the strength of the pinion shaft 7 is not

20 obtained. When the hardness exceeds 300 HV, the
toughness of the whole pinion shaft 7 is
deteriorated, the tool life in hobbing is
shortened, and a long time period is required for
the hobbing. Therefore, the hardness is set in

25 the above-mentioned range to allow strength to be

ensured and allow the productivity to be maintained and improved. The preferable lower limit value of the hardness of the shaft interior 81 is 270 HV, and the more preferable upper limit value thereof is 290 HV.

In the case of the above-mentioned pinion shaft 7, high wear resistance and high strength (static strength, fatigue strength, impact strength) can be achieved using a low-cost non-refined steel. Therefore, the pinion shaft 7 can be suitably used for a high-power electric power steering device of a pinion assist type that receives high stress and high surface pressure.

Although the present invention has been described in more detail by specific modes, those skilled in the art who have understood the above-mentioned contents will easily consider its change, modification, and equivalent. Therefore, the range of the present invention should be the scope of claims and the scope of its equivalent.

The present application corresponds to Japanese Patent Application No. 2004-119360 filed with the Japanese Patent Office on April 14, 2004, and the entire disclosure of the application

is incorporated herein by reference.

The present invention will be more specifically described by taking examples.

Examples and Comparative Examples

5   Steels in examples of the present invention and comparative examples, which have ingredients shown in Table 1, described below, were respectively melted and then formed into billets, and were hot rolled under a draft ratio of 15 %

10   at a temperature of not more than 800℃, to form a material composed of a round rod having a diameter of 23 mm. A non-refined steel that is the material was machined, to produce an intermediate for production having the shape of

15   a pinion shaft formed therein, and the intermediate for production was then subjected to high frequency quenching by high frequency heating to a temperature of 900 to 1000℃ and cooled to room temperature by water cooling,

20   thereafter, the intermediate for production was subjected to tempering processing at an atmospheric temperature of 150℃ and for a processing time of one hour, to form the hardened layer 80, thereby manufacturing pinion shafts in

25   the examples and the comparative examples. Each

of the pinion shafts was so adapted that the length thereof was 130 mm, the average diameter of a shaft section was 15 mm, and the outer diameter of a tooth section was 20 mm, and has five rows of

5   teeth.

A positive input static fracture test, a reverse input static fracture test, a reverse input impact fracture test, a positive input durability test, and a reverse input durability

10 test were carried out using the examples and the comparative examples. The Vickers hardnesses on surfaces of a pinion teeth forming section and the shaft section were measured, and the tooth form accuracy after gear cutting of the pinion teeth

15 was measured. As a result, the following results shown in Table 2 were obtained. Each of the tests will be specifically described.

In each of the examples and the comparative examples, the ratio D/R of the effective case

20 depth D in the tooth bottom 7b to the radius R of the tooth bottom 7b was 0.3, and the ratio d/r of the effective case depth d in the shaft sections 71 and 72 to the radius r of the shaft sections 71 and 72 was 0.3.

25 <u>Positive input static fracture test</u>

A tester as shown in Fig. 5 was used. Both ends of the housing 9 for holding the rack bar 8 meshed with the pinion shaft 7 in the example or the pinion shaft in the comparative example were respectively fixed to fixing supports 31. The rack bar 8 was fixed at its neutral position, and a driving torque was applied to the pinion shaft 7 from a rotary actuator 32 connected to the pinion shaft 7. The driving torque was increased, to lead to a fracture. Fracture strength (N·m) was measured. In Table 2, references ◯, △, and ✕ are as follows:

◯ : not less than 600 N·m

△ : not less than 400 N·m and less than 600 N·m

✕ : less than 400 N·m

Reverse input static fracture test

A tester as shown in Fig. 6 was used. Both ends of the housing 9 for holding the rack bar 8 meshed with the pinion shaft 7 in the example or the pinion shaft in the comparative example were respectively fixed to fixing supports 31 through mount rubbers 33. The pinion shaft 7 was fixed at its neutral position through a joint 34, an end of the rack bar 8 was pressed by a load cylinder

35 through a load cell 36, and a load was applied until a fracture sound (cracking sound) was confirmed. An output of an dynamic strain indicator 37 connected to the load cell 36 was

5   recorded on a recorder 38, to measure a fracture load (kN). In Table 2, references ○, △, and × are as follows:

○ : not less than 80 kN

△ : not less than 60 kN and less than 80 kN

10   × : less than 60 kN

Reverse input impact fracture test

A tester as shown in Fig. 7 was used. Both ends of the housing 9 for holding the rack bar 8 meshed with the pinion shaft 7 in the example or

15   the pinion shaft in the comparative example were respectively fixed to a pair of fixing arms 40 fixed to a fixing support 39. The housing 9 was raised and arranged with its end closer to the pinion shaft 7 located above. The pinion shaft

20   7 was fixed to a fixing support 41 at its neutral position. A receiving member 42 was fixed to an end, closer to the pinion shaft 7, of the rack bar 8.

A plumb bob 44 supported so as to be movable

25   up and down by a guide bar 43 was provided above

the receiving member 42, and a load cell 45 was fixed to the bottom of the plumb bob 44. The weight of the plumb bob 44 to which the load cell 45 was fixed was 0.98 kN. The plumb bob 44 and the load

5 cell 45 were dropped with the distance between the load cell 45 and the receiving member 42 set to 20 cm, to collide with the receiving member 42 and examine the number of times of drop until they are damaged.

10 A dynamic strain indicator 46 was connected to the load cell 45, and an output of the dynamic strain indicator 46 was recorded on an electromagnetic oscilloscope 47, to measure reverse input impact strength (kN × the number

15 of times). In Table 2, references $\bigcirc$, $\triangle$, and $\times$ are as follows:

$\bigcirc$: not less than 500 (kN × the number of times)

$\triangle$: not less than 200 (kN × the number of

20 times) and less than 500 (kN × the number of times)

$\times$: less than 200 (kN × the number of times)

Positive input durability test

A tester as shown in Fig. 8 was used. Both ends of the housing 9 for holding the rack bar 8

25 meshed with the pinion shaft 7 in the example or

the pinion shaft in the comparative example were
respectively fixed to fixing supports 54. Servo
actuators 55 were respectively connected to both
ends of the rack bar 8. A rotary actuator 58 was

5   connected to the pinion shaft 7 through a joint
56 and a torque meter 57, and a driving torque was
applied to the pinion shaft 7 by the rotary
actuator 58. The driving torque was set to 50 N·m,
and the number of repetitions was set to 30000 at

10   a frequency of 0.15 Hz. After the test was
terminated, an amount of wear of a meshed portion
with rack teeth was measured. In Table 2, large,
medium, and small references of the amount of wear
were as follows:

15   small amount of wear : not more than 20 μm
          medium amount of wear : more than 20 μm and
not more than 50 μm
          large amount of wear : more than 50 μm
Reverse input durability test

20   A tester as shown in Fig. 9 was used. Both
ends of the housing 9 for holding the rack bar 8
meshed with the pinion shaft 7 in the example or
the pinion shaft in the comparative example were
respectively fixed to fixing supports 59. The

25   pinion shaft 7 was fixed at its neutral position

through a joint 60, and an axial force was loaded
to the rack bar from a servo actuator 61 through
a tie rod 10 connecting with an end, closer to the
pinion shaft 7, of the rack bar. The axial force

5   loaded to the rack bar was set to 10 kN, and the
number of repetitions was set to 700000 at a
frequency of 5 Hz. After the test was terminated,
an amount of wear of a meshed portion with rack
teeth was measured. In Table 2, large, medium,

10   and small references of the amount of wear were
as follows:

small amount of wear : not more than 60 µm

medium amount of wear : more than 60 µm and
not more than 100 µm

15   large amount of wear : more than 100 µm

Tooth form accuracy measurement test

A tooth form error after gear cutting of
pinion teeth in each of the pinion shafts in the
examples and the comparative examples was found.

20   Specifically, the maximum error in all the teeth
(all teeth Max.) was found. In Table 2, large,
medium, and small references of the maximum error
were as follows:

small maximum error : not more than 10 µm

25   medium maximum error : more than 10 µm and

not more than 30 µm

large maximum error : more than 30 µm

Table 1 (mass%)

No.	C	Si	Mn	P	S	Mo	B	Ti	N	Others	Ceq	f-value
Examples												
1	0.50	0.21	0.78	0.016	0.017	0.17	0.0015	0.04	0.008	Cr: 0.22	0.81	0.35
2	0.54	0.26	0.74	0.016	0.015	0.17	0.0016	0.045	0.008		0.85	0.00
3	0.52	0.45	1.10	0.015	0.015	0.20	0.0015	0.04	0.008	Cr: 0.30	0.93	0.12
4	0.45	0.25	1.00	0.015	0.015	0.23	0.0015	0.04	0.008		0.82	0.50
5	0.49	0.28	0.82	0.016	0.015	0.19	0.0013	0.04	0.009	Cu: 0.30, Ni: 0.25, Cr: 0.18, Ta:0.06, Al: 0.05	0.81	0.23
Comparative Examples												
1	0.45	0.25	0.70	0.015	0.015	0.23	0.0015	0.04	0.008		0.78	0.75
2	0.41	1.10	0.55	0.015	0.015	0.26	0.0015	0.04	0.008		0.80	1.02
3	0.55	0.65	1.10	0.015	0.015	0.20	0.0016	0.04	0.008		0.98	0.03
4	0.60	0.24	0.85	0.016	0.015	0.20	0.0019	0.04	0.010		0.92	0.12
5	0.51	0.25	0.83	0.015	0.015	0.12	0.0015	0.04	0.008		0.78	0.42
6	0.49	0.30	0.60	0.015	0.015	0.30	0.0015	0.04	0.008		0.82	0.86
7	0.51	0.65	0.75	0.017	0.018	0.21	0.0002	0.035	0.010		0.86	0.44
8	0.53	0.08	0.82	0.014	0.017	0.16	0.0078	0.11	0.018		0.81	0.31

Table 2

37

	Static breakdown test		Reverse input impact breakdown	Endurance test		Tooth profile error	Hv
	Normal input	Reverse input		Normal input	Reverse input		
Example 1	○	○	○	Smaller	Smaller	Smaller	715
Example 2	○	○	○	Smaller	Smaller	Smaller	718
Example 3	○	○	○	Smaller	Smaller	Smaller	760
Example 4	○	○	○	Smaller	Smaller	Smaller	650
Example 5	○	○	○	Smaller	Smaller	Smaller	709
Comparative Example 1	△	△	△	Medium	Medium	Medium	620
Comparative Example 2	△	△	×	Greater	Greater	Medium	570
Comparative Example 3	△	△	×	Smaller	Smaller	Medium	730
Comparative Example 4	○	○	×	Smaller	Smaller	Medium	770
Comparative Example 5	△	△	×	Medium	Medium	Greater	720
Comparative Example 6	○	○	○	Medium	Medium	Greater	705
Comparative Example 7	△	△	×	Smaller	Smaller	Smaller	718
Comparative Example 8	△	△	△	Smaller	Smaller	Smaller	734

From the results shown in Table 2, in any of the examples 1 to 5 in the present invention, the positive input static fracture strength was not less than 600 N·m, the reverse input static

5   fracture strength was not less than 80 kN, the amount of wear in the positive input durability test was not more than 20 μm, the amount of wear in the reverse input durability test was not more than 60 μm, the surface hardness was 650 to 760

10 HV, and the tooth form error was as small as 10 μm or less.

Contrary to this, in the comparative example 1 in which Ceq was 0.78, which was somewhat lower than those in the examples 1 to 5 in the present

15 invention, the surface hardness was 620 HV, which was somewhat lower, the static fracture strength and the reverse input impact fracture strength were lower, the amount of wear in the durability test was larger, and the tooth form error was

20 larger, as compared with those in the examples 1 to 5 in the present invention.

In the comparative example 2 in which the C content was 0.41 % by mass, which was somewhat lower, the Si content was 1.10 % by mass, which

25 was significantly higher, and the f value was

1.02, which was higher, as compared with those in the examples 1 to 5 in the present invention, the surface hardness was 570 HV, which was significantly lower, the static fracture

5 strength was lower, the reverse input impact fracture strength was significantly lower, the amount of wear in the durability test was larger, and the tooth form error was larger, as compared with those in the examples 1 to 5 in the present

10 invention.

In the comparative example 3 in which Ceq was 0.98, which was higher than those in the examples 1 to 5 in the present invention, the static fracture strength was lower, the reverse input

15 impact fracture strength was significantly lower, the amount of wear by the durability test was larger, and the tooth form error was larger, as compared with those in the examples 1 to 5 in the present invention.

20 In the comparative example 4 in which the C content was higher than those in the examples 1 to 5 in the present invention, the reverse input impact fracture strength was significantly lower, and the tooth form error was larger, as

25 compared with those in the examples 1 to 5 in the

present invention.

In the comparative example 5 in which the Mo content was somewhat lower than those in the examples 1 to 5 in the present invention, and Ceq

5 was somewhat lower than those in the examples 1 to 5 in the present invention, the static fracture strength was somewhat lower, the reverse input impact fracture strength was significantly lower, the amount of wear by the durability test

10 was larger, and the tooth form error was larger, as compared with those in the examples in the present invention.

In the comparative example 6 in which the Mo content was higher than those in the examples 1

15 to 5 in the present invention, the amount of wear by the durability test was larger, and the tooth form error was significantly larger, as compared with those in the examples 1 to 5 in the present invention.

20 In the comparative example 7 in which the Si content was higher than those in the examples 1 to 5 in the present invention, and the B content was lower than those in the examples 1 to 5 in the present invention, the static fracture strength

25 (corresponding to torsional strength) was lower,

and the reverse input impact fracture strength was significantly lower, as compared with those in the examples 1 to 5 in the present invention.

In the comparative example 8 in which the Ti content and the N content were higher than those in the examples 1 to 5 in the present invention, the static fracture strength (corresponding to torsional strength) and the reverse input fracture strength were lower, as compared with those in the examples 1 to 5 in the present invention.

Hardened layer ratio test 1

Examples 6 to 11, in which only the conditions of induction hardening in the example 1 were varied, to make the effective case depth D in the tooth bottom 7b differ to make only the ratio (hardened layer ratio) D/R of the effective case depth D in the tooth bottom 7b to the radius R of the tooth bottom 7b differ, as shown in Table 3, described below, were prepared. When the same positive input static fracture test and tooth form accuracy measurement test as the foregoing were carried out, to obtain results shown in Table 3.

Table 3

	Hard layer ratio D/R	Normal input static breakdown test	Tooth profile error
Comparative Example 9	0.05	×	Smaller
Example 6	0.1	Δ	Smaller
Example 7	0.2	○	Smaller
Example 1	0.3	○	Smaller
Example 8	0.4	○	Smaller
Example 9	0.5	○	Medium
Example 10	0.6	○	Greater

According to the results shown in Table 3, it became clear that sufficient torsional strength was obtained if the ratio D/R was not less

5   than 0.1 (example 1 and examples 6 to 10), while higher torsional strength (static fracture strength) was obtained if the ratio D/R was not less than 0.2 (example 1 and examples 7 to 10). Further, it became clear that the tooth form error

10   fell within an allowable level if the ratio D/R was not more than 0.5 (example 1 and examples 6 to 9), while the tooth form error could be even smaller if the ratio D/R was not more than 0.4 (example 1 and examples 6 to 8).

15   As a result, it became clear that preferable results were obtained in both the torsional

strength and the tooth form error (maximum error) if the ratio D/R was in a range of 0.1 to 0.5. Further, it became clear that more preferable results were obtained in both the torsional

5   strength and the tooth form error (maximum error) if the ratio D/R was in a range of 0.2 to 0.4.

Hardened layer ratio test 2

Examples 11 to 15, in which only the conditions of induction hardening in the example

10   1 were varied, to make only the ratio (hardened layer ratio) d/r of the effective case depth d in the shaft sections 71 and 72 to the radius r of the shaft sections differ, as shown in Table 4, described below, were prepared. The same positive

15   input static fracture test as the foregoing and a torsional fatigue test as shown in the following were carried out, to obtain results shown in Table 4.

Torsional fatigue test: A torsional fatigue test

20   using a test specimen for torsional fatigue test (a smooth test specimen having a diameter of 12 mm and having a length of 100 mm in its parallel portion) as a sample was carried out, to evaluate the test specimen in time strength of 10^5 cycles.

25   ○ : not less than 650 MPa

△ : not less than 500 MPa and less than 650 MPa

✕ : less than 500 MPa

Table 4

	Hard layer ratio d/r	Normal input static breakdown test	Torsional fatigue test
Comparative Example 10	0.03	△	×
Example 11	0.05	△	△
Example 1	0.3	○	△
Example 12	0.35	○	○
Example 13	0.5	○	○
Example 14	0.6	○	△
Example 15	0.7	○	×

5   According to the results shown in Table 4, it became clear that if the ratio d/r was 0.05 to 0.6 (example 1 and examples 11 to 14), static torsional strength (static fracture strength) and torsional fatigue strength, which were not

10   less than allowable levels, were obtained. That is, when the ratio d/r exceeded 0.6 (example 15), effects on static torsional strength and torsional fatigue strength were saturated, while the toughness was deteriorated. When the ratio

15   d/r was 0.6, it would appear that the toughness was liable to be lower, as compared with that in

a case where the ratio d/r was 0.5. Consequently,

it was more preferable that the upper limit of the

ratio d/r was 0.5. Further, it became clear that

if the ratio d/r was 0.35 to 0.5 (examples 12 and

5   13), high static torsional strength and high

torsional fatigue strength were obtained.